

## Fast Search Techniques for High Energy Pulsars

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**Abstract.** Modified versions of two “standard” pulsar search techniques are presented that allow large-scale searches for pulsations in long duration high-energy data sets using relatively modest amounts of computer time. For small numbers of photons ( $N_{phot} \lesssim 10^4$ ), optimized brute-force epoch folding searches are preferred. For larger numbers of photons, advanced Fourier domain acceleration searches are used. Using these techniques, my collaborators and I have searched *Chandra* observations of the Cas A supernova remnant (SNR) point source and the isolated neutron star RX J1856.5–3754 for pulsations, and confirmed the 65.6 ms pulsar in the 3C 58 SNR during a blind search of archival *RXTE* data.

### 1. Introduction

Sensitive searches for pulsars in long duration high-energy (i.e. X-ray and  $\gamma$ -ray) observations are difficult. For relatively short observations ( $T_{obs} \lesssim 20$  ks) all known isolated pulsars can be assumed to have a constant spin period during the observation. In this limiting case, searches for relatively bright pulsars are usually implemented using simple epoch folding or a standard Fourier analysis (e.g. Leahy et al., 1983; van der Klis, 1989). When  $T_{obs}$  is long, however, the spin-down of young high-energy pulsars becomes important. The corresponding change in frequency during an observation can make these pulsars invisible to traditional search techniques.

Another difficulty involved in searching very long observations (i.e. many days) is the extraordinarily large number of independent trials required for a blind search. For epoch folding searches that cover a wide range of both frequency  $f$  and frequency derivative  $\dot{f}$ , the computational complexity is  $\propto N_{phot}T_{obs}^2$ , or  $\propto T_{obs}^3$  for a source of constant flux. Advanced Fourier analyses of very long time series (i.e.  $(2 - 20) \times 10^8$  points where the photons have been binned) have been carried out by a few groups (e.g. Middleditch et al., 2000; Chandler et al., 2001) and are, in general, more efficient due to the use of the FFT (computational complexity  $\propto T_{obs}^2 \log T_{obs}$ ). The difficulties involved in computing many FFTs of this size, however, have relegated such analyses to those with access to large-scale super-computing.

The techniques that I describe here allow large-scale blind searches of very long high-energy observations to be carried out on modest (albeit modern) workstations or inexpensive workstation clusters.

## 2. Optimized Epoch Folding ( $N_{phot} \lesssim 10^4$ )

Epoch folding involves placing each event (i.e. photon) into one of a relatively small number of pulse phase bins (usually 2–20) by calculating the exact pulse phase of the event based on a trial pulsar ephemeris (e.g.  $f$  and  $\dot{f}$ ) and an arbitrary starting phase of the profile (i.e. phase zero). For each trial profile, one of many possible (but preferably computationally “cheap”) statistical tests is performed on the profile to determine if it shows a pulsed signal or not.

For blind searches, a large range of  $f$  and  $\dot{f}$  must be covered at high resolution in both the  $f$  and  $\dot{f}$  directions. In order to maximize sensitivity to low duty-cycle (i.e. narrow) pulse profiles, one must oversample the Independent Fourier Spacing ( $1/T_{obs}$ ) in frequency and the equivalent independent spacing in  $\dot{f}$  ( $\sim 6/T_{obs}^2$ ) by a factor of 4 or more.

More advanced searches also attempt to match the complexity of the expected pulse shape with an appropriate number of pulse phase bins at the optimal starting phase of the profile. For example, sinusoidal profiles only require 2 properly phased bins for good sensitivity, but narrow pulse profiles are best detected if a single phase bin has the same width as the pulse and is centered on it. Unfortunately, searching over various numbers of phase bins and starting phases greatly increases the computer time required in an already costly search.

I have made modifications to the Bayesian method of epoch folding presented by Gregory & Loredo (1992, 1996) that incorporates everything described above in an efficient manner. These modifications allow brute force searches of “reasonable” high-energy data sets in a few weeks or less on a fast workstation (i.e.  $N_{phot} \sim 1000$  photons,  $T_{obs} \lesssim 30$  days,  $0 < f \lesssim 500$  Hz,  $|\dot{f}| \lesssim 10^{-9}$  Hz s $^{-1}$ ).

The calculations required to search over various numbers of phase bins and starting phases have been reduced dramatically from the exact method described in Gregory & Loredo (1992). The basic idea is to initially fold the data into 60 or 120 phase bins and then combine various numbers of these bins (i.e. 2, 3, 4, 5, 6, 10, 12, 15, 20 bins) in an efficient manner at each of the 60 or 120 starting phases in order to maximize the signal-to-noise.

For very long duration observations, huge savings in CPU time can be had by searching the photons in a hierarchical manner and accepting some loss in sensitivity. Since for a search of a continuously sampled observation of a source with constant flux the required number of operations is  $\propto T_{obs}^3$ , searching only a short but continuous part of the data takes much less time than searching the full observation (the number of photons and required resolution in  $f$  and  $\dot{f}$  are reduced significantly). Candidates above a very low threshold (say the top few percent) in this initial search are then examined using twice as many photons (or approximately twice the duration) at a correspondingly finer resolution. This process continues until all the photons are examined and the full resolution of the data is reached around the candidate.

My collaborators and I have recently applied these techniques to brute-force searches of *Chandra* observations of two very interesting X-ray sources: the point source found near the center of the Cas A SNR (Tananbaum, 1999) and the isolated neutron star RX J1856.5–3754 (Walter, Wolk, & Neuhäuser, 1996). Murray et al. (2002a) searched a 50 ks HRC-S observation (OBSID 1857) from the Cas A point source and reported no convincing candidates. More recently,

we have searched the follow-up 50 ks observation (OBSID 1038) of Cas A and could neither find any convincing new candidates nor confirm any of the low significance candidates from the earlier search (manuscript in preparation). A similarly unsuccessful search for pulsations (and a corresponding 99% confidence level upper limit to pulsations of 4.5%) from the 450 ks Director’s Discretionary Time observation of RX J1856.5–3754 was reported by Ransom, Gaensler, & Slane (2002).

### 3. Fourier-Domain Acceleration Searches ( $N_{phot} \gtrsim 10^3$ )

When the observed number of photons is too large to allow efficient epoch folding searches to be conducted, the photons can be binned into a time series and searched using acceleration searches (i.e.  $\dot{f}$  is constant during the observation) instead. Time domain acceleration searches have been used by numerous groups for some time (e.g. Middleditch & Kristian, 1984) and involve either re-sampling or re-binning the original uncorrected data to account for a non-zero  $\dot{f}$ . Each time series corresponding to a different  $\dot{f}$  trial then requires a long FFT and a subsequent search for pulsations. Unfortunately, FFTs of very long time series are difficult to compute (e.g. Chandler et al., 2001).

By using Fourier domain acceleration search techniques (Ransom, 2001), only a single FFT of the original time series is required. All  $\dot{f}$  trials are computed by correlating complex template responses with the raw Fourier amplitudes from the original FFT (i.e. matched filtering in the Fourier domain). The single long FFT that is required can be easily computed using out-of-core memory FFT techniques on even modest workstations. The subsequent Fourier domain acceleration search is very efficient since the matched filtering is inherently memory local and easily computed using short FFTs.

My collaborators and I have used a Fourier domain acceleration search code that includes Fourier interpolation (to minimize the effects of “scaloping”, e.g. van der Klis, 1989) and harmonic summing (to improve sensitivity to low duty-cycle pulsations) to successfully search numerous long radio observations of globular clusters and X-ray observations of potential X-ray pulsars. New pulsars detected using these methods include the binary millisecond radio pulsar PSR J1807–2459 in globular cluster NGC6544 (Ransom et al., 2001) and a probably isolated 4.714 ms pulsar in Terzan 5 (Ransom, 2001).

Recently, Murray et al. (2002b) used these techniques to confirm the new 65.6 ms X-ray pulsar discovered with *Chandra* in the 3C 58 SNR and measure its spin-down characteristics. We conducted a blind Fourier domain acceleration search on an archival 36 ks *RXTE* observation (OBSID 20259-02-01-00 with 20.6 ks on-source) and uncovered a  $\sim 6.4\sigma$  candidate as a sum of 8 harmonics (the strongest having only  $\sim 13$  times the local mean power — showing the need for a harmonic sum). The pulse profile from the *RXTE* observation is shown in Figure 1. By comparing the measured pulse periods from the *RXTE* and *Chandra* data we were able to measure the period derivative ( $1.93 \times 10^{-13}$ ), spin-down  $\dot{E}$  ( $\sim 2.7 \times 10^{37}$  ergs s $^{-1}$ ), surface magnetic field strength ( $\sim 3.6 \times 10^{12}$  gauss), and characteristic age ( $\sim 5380$  y), showing that it is a surprisingly “normal” young pulsar.

